pp. 107-117

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*An Equation of State for Calculating the Thermodynamic Properties of Helium at Low Temperatures**

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8

ABSTRACT 17169

A new equation of state for helium gas with six adjustable constants is presented. This relation is adequate for the representation of the P-V-T data and for the calculation of the entropy and enthalpy for a range of temperatures from 20 to 300 K, with pressures to 100 atm. A comparison of calculated volumes with the original data indicates an average arithmetic deviation of 0.07 percent and maximum deviations of 0.5 percent. A comparison of calculated pressures with original data indicates about the same average and maximum deviations. A temperature-entropy chart and a compressibility factor chart have been prepared from values calculated by this equation of state. Values of density, enthalpy and entropy, are tabulated with temperature and pressure as independent arguments.

1. INTRODUCTION

The development of a new equation of state for helium over an extensive range of temperature and pressure arose from the need for a reasonable mathematical expression which would be adequate, not only for the representation of pressure, specific volume, and temperature values, but also for the calculation of some of the derived thermodynamic properties over an extended range of values. The increased use of high speed digital computers for the analysis of thermodynamic systems has notably increased the need for such equations. The virial expansions were the only relations previously available for representation of the P-V-T data at low temperatures to the degree of accuracy and with the extended range achieved by the equation presented here. The virial equations do not lend themselves to the direct calculation of the thermodynamic properties.

Beattie and Bridgeman [1] reported an average deviation between calculated and experimental values for their equation of state of 0.133 percent, but limited the maximum density to .04 g/cm^3. Akin [2] reported density deviations of as much as 5 to 10 percent for values above the critical density predicted by the Beattie-Bridgeman equation. The equation of state presented here, however, can be used for obtaining accurate P-V-T values for the total range for which experimental data is available; i.e., to 100 atm pressure, which includes values to twice critical density.

Entropy and enthalpy values calculated from this equation of state with the zero pressure heat capacity taken from the literature are in agreement with values determined from other sources for a range of temperature from 20 to 300 K with pressures to 100 atm. In addition, the equation predicts the Boyle temperature, the Joule-Thomson inversion temperature, the Joule-Thomson coefficients and the second virial coefficients closely enough to lend additional credence to the validity of the equation. At increasing pressures, the equation in its present form is satisfactory except at temperatures below 20 K (See Table 1). It has not been evaluated for temperatures above 300 K. The behavior of this equation at higher pressures is unknown, since adequate experimental data over 100 atm are limited.

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Code none

TABLE 1

COMPARISON OF CALCULATED VALUES OF SPECIFIC VOLUME WITH MEASURED VALUES

a. Comparison with Zelmanov's Data:

$$\% \text{ Difference} = \frac{V_{Zel} - V_{(2)}}{V_{Zel}} \times 100$$

Press. atm	Temperature, K 8	10	12	14	16	18	20
0.5	−2.0	0.6	−0.4	−0.1	0	−0.1	0.1
1	−4.8	−1.5	−0.7	−0.1	0.1	0.1	0
2	−5.1	−3.1	−1.3	−0.5	−0.1	0	0
5	−27.2	−7.9	−4.1	−1.6	−0.7	−1.2	−0.3
10		−22.0	−6.0	−3.6	−1.4	−0.6	0.2
15			−8.6	−4.8	−2.5	−0.3	−0.4
20			−5.0	−4.1	−2.6	−1.3	−0.7
25			−0.4	−2.9	−2.6	−1.5	−0.5
30			5.9	1.8	−1.1	−0.9	−0.5
40			12.1	6.5	3.1	−0.4	−0.3
50			14.8	8.7	4.3	1.1	−0.9
60			18.2	12.2	7.0	3.1	1.4

Differences above the heavy line are less than 1%.

b. Comparison with Lounasmaa's Data:

$$\% \text{ Difference} = \frac{V_{Lou} - V_{(2)}}{V_{Lou}} \times 100$$

Press. atm	% Diff.	Press. atm	% Diff.	Press. atm	% Diff.	Press. atm	% Diff.
14 K		16 K		18 K		20 K	
3.8	−1.2	4.4	−0.6	5.0	−0.2	5.6	0
7.4	−2.2	8.7	−1.3	9.9	−0.9	11.2	−0.4
10.9	−3.4	13.0	−2.0	14.9	−1.4	16.9	−1.0
14.6	−3.5	17.4	−2.1	20.3	−1.4	23.1	−1.0
18.6	−2.8	22.4	−1.1	26.2	−0.5	29.9	−0.4
23.1	−1.2	28.0	0.1	32.8	0.3	37.6	0.1
23.8	1.0	34.4	1.4	40.5	1.2	36.6	0.9
34.9	3.7	42.3	3.0	49.7	2.2	57.2	1.5
43.1	6.2	51.9	4.4	60.8	3.0	69.8	1.9
53.9	8.3	64.3	5.6	74.8	3.7	85.3	2.3
68.0	9.4	80.3	6.3	92.6	4.2		
76.6	9.6	89.8	6.4	103.0	4.3		
86.4	9.5	100.6	6.4				

The principal source of data used in the development of this equation was Helium [3] by Keesom. The second and third virial coefficients were summarized by Keesom as a result of a comprehensive survey of the literature prior to 1941. These virial coefficients were adopted by Keesom in subsequent calculations and resulted in his widely accepted T-S Diagram for Helium [4]. It should be noted, however, that Keesom's T-S Diagram was subsequently modified below 20 K by the additional data from Zelmanov [5]. Keesom listed these coefficients for the virial expansion of the form:

$$PV = A + B/V + C/V^2 + \ldots, \tag{1}$$

for temperatures from 2.6 to 570 K.

With the use of Keesom's coefficients, P-V-T values have been calculated from (1) and compared with both the experimental data listed by Keesom [6 to 13] and the more recent data of Zelmanov [14, 5] and Lounasmaa [15]. This comparison showed that these virial coefficients accurately represented the experimental data from 20 to 300 K. They were inadequate, however, for higher pressures at temperatures below 20 K. (See Table 2). The P-V-T values calculated from (1) will hereafter be referred to as virial data.

2. THE EQUATION OF STATE FOR HELIUM

The equation of state that has been developed is explicit in volume, a form particularly useful in the

TABLE 2

COMPARISON OF VIRIAL VALUES OF SPECIFIC VOLUME WITH MEASURED VALUES

a. Comparison with Zelmanov's Data:

$$\% \text{ Difference} = \frac{V_{virial} - V_{Zel}}{V_{virial}} \times 100$$

Press. atm	Temperature, K 8	10	12	14	16	18	20
5	−0.30	0.04	−0.16	−0.13	−0.004	−0.06	−0.17
10	25.83	7.95	−0.20	−0.53	−0.01	0.13	0.47
20		10.94	1.61	−0.91	−1.08	−0.62	0.40
30		19.83	8.63	3.06	−0.69	−0.79	−0.63
40			13.16	6.68	2.95	0.03	−0.73
50			15.97	9.05	4.12	0.80	−1.35
60				13.33	7.52	3.22	−1.34

Differences above the heavy line are less than 1%.

b. Comparison with Lounasmaa's Data:

$$\% \text{ Difference} = \frac{V_{virial} - V_{Lou}}{V_{virial}} \times 100$$

Press. atm	% Diff.	Press. atm	% Diff.	Press. atm	% Diff.
18 K		19 K		20 K	
5	0.93	5.3	0.93	5.6	0.92
9.93	−0.41	43.55	−0.10	11.21	−0.16
14.95	−1.69	53.45	1.38	16.95	−1.46
20.26	−2.39	98.8	6.18	23.1	−1.03
26.20	−1.99			29.95	−1.78
32.85	−1.25			37.95	−1.18
49.7	1.53			46.6	−1.18
60.85	3.35			57.20	1.12
74.8	5.29			59.75	2.51
92.65	7.13			85.25	3.91
103.05	7.67				

calculation of the derived thermodynamic properties. This equation of state, employing six adjustable coefficients is

$$V=\frac{RT}{P}+\frac{E}{(P+1)^{0.5}}+F-\exp\left[-(A+BP)T-(CP+D)\right] \quad (2)$$

where T is temperature in K, P is pressure in atm, and V is the Amagat volume, which is the ratio of specific volume to the specific volume at standard conditions, (0 C and 1 atm), i.e.,

$$V(\text{Amagat})=\frac{v}{v_0}=\frac{\text{observed specific volume}}{\text{specific volume at standard conditions}}.$$

The value used here for v_0 is Keesom's recommended value 5603.1 cm^3/g. The values of the coefficients for (2) are:

$A = +0.0553629603$ (K^{-1}),
$B = -0.0002507030379$ (atm^{-1} K^{-1}),
$C = +0.02442567441$ (atm^{-1}),
$D = +6.257793015$,
$E = -0.0001900546554$ (Amagat $atm^{0.5}$),
$F = +0.0005502201182$ (Amagat).

These coefficients were used in all subsequent calculations. (The specific volumes will have the same order of accuracy when they are calculated with the above coefficients rounded to four significant places.) The value of R, the ideal gas constant used in this equation is $R = P_0V/T_0 = 1/T_0 = 1/273.15$ (Amagat atm/K).

The coefficients A, B, C, D and E, F were determined by fitting (2) to virial data with the aid of two separate least squares programs on a digital computer. To determine E and F, it was first noted from a graphical study of the P-V-T values of the virial data that the isobars ($P = C$) on V-T coordinates were nearly linear over a large range of values. As a first approximation, the equation of state was written as

$$V = a(P)T + b(P), \quad (3)$$

where $a(P) = (\partial V/\partial T)_P$, the slope of the isobar, and $b(P)$, the zero temperature intercept, were functions of pressure only. An evaluation of these coefficients, by a least squares fit of the virial data, indicated that they could by adequately approximated by the relations

$$a(P)=\frac{R}{P}, \quad (4)$$

$$b(P)=\frac{E}{(P+1)^{0.5}}+F. \quad (5)$$

The slope, $(\partial V/\partial T)_P = R/P$, is of course the value for the ideal gas. The first approximation of an equation of state was then obtained as

$$V=\frac{RT}{P}+\frac{E}{(P+1)^{0.5}}+F. \quad (6)$$

Deviation of the specific volume in the virial data (denoted by V_{virial}) from this approximate value (denoted by $V_{(6)}$) was then determined as

$$V_r=V_{virial}-V_{(6)}=-\exp\left[-(A+BP)T-(CP+D)\right]. \quad (7)$$

The coefficients A, B, C, and D were then determined by fitting (7) to virial data with the aid of a different least squares program.

For the determination of E and F, 250 points from Keesom's virial data in the temperature range 18 to 300 K and the pressure range 0.1 to 100 atm were used. The determination of A, B, C, and D was accomplished by using the same 250 points, with the addition of 37 points from Lounasmaa's P-V-T data and 34 points from Zelmanov's P-V-T data in the 18 to 20 K region. The final equation of state (2) is the sum of (6) and (7).

3. EVALUATION OF THE EQUATION OF STATE

A comparison of values of specific volumes calculated with the equation of state was made between 20 and 300 K with 237 of the virial data points which were used in the determination of the coefficients for the equation. The average arithmetic deviation was 0.07 percent, and the maximum deviation 0.5 percent. At 20 K, these calculated values were also compared to twelve data values from Zelmanov and seven values from Lounasmaa. The average deviation was less than 0.3 percent, and the maximum deviation 1.4 percent. A comparison of the pressures, however, would be a more critical measure of the deviation than the comparison of the specific volumes at high densities. Therefore, a similar comparison was made for values of pressure, which resulted in an average arithmetic deviation from virial data for temperatures of 20 to 300 K of 0.1 percent, with a maximum deviation of 0.6 percent. At 20 K, the average deviation from the data of Zelmanov and Lounasmaa was 0.3 percent, and the maximum deviation 1.3 percent (except at 60 atm and 20 K where the deviation was 2.3 percent). An exception in these comparisons of virial data occurred at 30 K and 100 atm. At this point, the volume deviation was 0.6 percent and the pressure deviation 1.0 percent. The values of pressure exhibiting the larger deviations were also observed at the same temperatures and pressures as the larger values of deviations for specific volume.

The data predicted by this equation of state were also compared to the original data referenced by Keesom, which include a total of 230 experimental points between 20 and 300 K. The average deviation of the calculated specific volumes from the experimental specific volumes was 0.2 percent. Values of entropy differences between 120 states, in the temperature and pressure range of 20 to 300 K and 0.1 to 100 atm, were also calculated from this equation and compared to corresponding differences from Keesom's T-S diagram. In this comparison, 92 percent of the values agreed within one percent and no deviations greater than three percent were observed. This agreement was within the accuracy with which Keesom's diagram could be read.

4. ANALYTICAL TESTS OF THE EQUATION OF STATE

Additional conditions that may be imposed on an equation of state with respect to its general form have also been investigated. The results of these investigations, enumerated below, indicate that this equation does approximate rather well such conditions as are pertinent within the range of variables for which validity of the equation is claimed. These conditions are as follows:

1) It is important that an equation of state reduce to the ideal gas equation as the pressure approaches zero or as temperature becomes infinite. This condition is satisfied by (2). (The importance of this condition is further illustrated in Section 5).

2) At the critical point certain partial derivatives should vanish, i.e., the partial derivative $(\partial P/\partial V)_T$ as well as higher order derivatives of P and V should be zero. Although the first derivative for this equation is not zero, the higher order derivatives are zero. The critical temperature, however, is well below the minimum temperature for which this equation will predict satisfactory values.

3) An isotherm of maximum slope of the Z-P diagram as pressure approaches zero is predicted by

$$\lim_{P\to 0} \left(\frac{\partial^2 Z}{\partial P \partial T}\right) = 0 \,, \tag{8}$$

and the temperature for this limiting isotherm for the equation of state is 44.1 K. The Z-P chart illustrates this with a maximum slope for isotherms near this value at pressures below 20 atm. This value may also be predicted from the second virial coefficients from Keesom as occurring at about 45 K.

4) The Boyle temperature, defined by

$$\lim_{P\to 0} \left(\frac{\partial Z}{\partial \rho}\right)_T = 0 \,, \tag{9}$$

is predicted by the equation of state as 30.1 K whereas a value of 25.2 K is given by Keesom.

5) The Joule-Thomson coefficients $\mu = (\partial T/\partial P)_H$, calculated from the expression

$$\mu = \frac{1}{C_P}\left[T\left(\frac{\partial V}{\partial T}\right)_P - V\right] , \tag{10}$$

have also been evaluated with the equation of state and are compared with the experimental Joule-Thomson data for helium by Roebuck and Osterberg [16]. These experimental values have been corrected for the error in pressure measurement reported in a later paper by Roebuck and Osterberg [17]. Table 3 illustrates the agreement between these calculated and observed values. Values of heat capacity, C_P, used in this calculation are from Zemansky [18].

6) The Joule-Thomson inversion temperature at zero pressure calculated from the equation of state is 55.5 K which compares favorably with the value of 50.5 K given by Keesom. The calculated value of this inversion temperature at 1 atm, is 51.0 K. Roebuck and Osterberg, however, report a value of 23.6 K at one atmosphere while Zemansky reports that this value occurs between 25 and 60 K.

7) The Joule coefficients, $\eta = (\partial T/\partial P)_U$, calculated from the expression

$$\eta = \left[\frac{T(\partial V/\partial T)_P + P(\partial V/\partial P)_T}{C_P - P(\partial V/\partial T)_P}\right], \tag{11}$$

have also been evaluated with the equation of state and C_P values from Zemansky. These are compared with the Joule coefficient values determined from experimental measurements and reported by Roebuck and Osterberg [19]. The Experimental data have been corrected for the same pressure error noted in item 5 above. Table 3 illustrates the agreement between these calculated and observed values.

The above conditions are rather severe tests of an equation of state. The relatively good agreement with which these values are predicted by this equation is notable. An adjustment of the second term of the equation of state $[E/(P+1)^{0.5}]$ would make it possible to satisfy even more closely the above conditions, without reducing the accuracy with which the properties may be calculated. Instead of the constant 1 in the denominator of this second term, 0 and 0.1 also have been used to calculate the specific volume. The result showed no significant differences in the values of the specific volume. The unit constant value is recommended, however, because the equation may then be easily expressed as a power series in pressure and this expansion may then be used to obtain an expression for the second virial coefficient. A preliminary examination of this relation indicates that a more exact prediction of the above conditions could be effected by replacing this unit constant with a function of temperature.

5. THE CALCULATION OF THERMODYNAMIC PROPERTIES

The derived thermodynamic properties for helium were calculated from the equation of state with the zero pressure heat capacity C_P^0 given by Rossini [20]. The calculation of the entropy and enthalpy differences along isotherms from the equation of state made use of the analogy between the real and the ideal gas in the limit as pressure approaches zero. This calculation of entropy and enthalpy requires the extrapolation of the equation of state from a few tenths of an atmosphere to zero pressure. Both the form of this equation at $P = 0$, and the accuracy with which it predicts P-V-T values at low pressures indicate that this extrapolation is proper. The value of C_P^0 given by Rossini is constant for this range of temperature. The resulting equation for entropy is:

$$S_{P,T} = S^*_{T_0} + C_P^0 \ln\frac{T}{T_0} - J\left\{ R\ln\frac{P}{P_1} + \left[-\frac{A}{BT+C}\left(\exp[-(BT+C)P]-1\right) + \frac{B}{(BT+C)^2}\left(-[BTP+CP+1]\exp[-(BT+C)P]+1\right)\right] \exp[-(AT+D)] \right\}, \quad (12)^\dagger$$

$S^*_{T_0}$ = 29.677 Joules/g K is an arbitrary datum value for an ideal gas entropy at an arbitrary pressure and temperature; T_0 = 273.15 K and P_1 = 1 atm are the temperature and pressure chosen for the datum in the calculation of the following tables and diagrams; C_P^0 = 5.1936 Joules/g K is derived from the value reported by Rossini; J = 567.55 Joule/g Amagat atm.

Using the equation of state and the above constants the enthalpy is given by:

$$H_{P,T} = H'_{T_0} + C_P^0 T + J\left\{ 2E\left[(P+1)^{0.5}-1\right] + FP + \frac{\exp[-(AT+D)]}{BT+C} \times \left[\left(\exp[-(BT+C)P]-1\right)(1+AT) + \frac{BT}{BT+C}\left([BTP+CP+1]\exp[-(BT+C)P]-1\right)\right]\right\}, \quad (13)^\dagger$$

where $H'_{T_0} = H^*_{T_0} - C_P^0 T_0$; $H^*_{T_0}$ = 1428.3 Joules/g is the arbitrary datum for the ideal gas enthalpy; T_0 = 273.15 K, and P = 1 atm are the temperature and pressure chosen for the datum in the calculation of the following tables and diagrams.

Equations (2), (12) and (13) were used in constructing the Compressibility Factor Chart and the Temperature-Entropy Chart and in calculating the tabular values of the thermodynamic properties. The T-S and H-S diagrams reported by Mann and Stewart [18] are suggested for properties of helium below 20 K. Although the datum values in their charts are different from the values used here, the diagrams are otherwise consistent.

†The equation of state is expressed in terms of Amagat volume, which is a dimensionless term. In equation (2) the implied dimensions of the final term $\exp[f(T,P)]$ are Amagats. This Amagat dimension is then also implied in corresponding terms on equations (12) and (13). These equations will then exhibit a consistency with the expressed units of J.

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TABLE 3

COMPARISON OF EXPERIMENTAL* AND CALCULATED VALUES OF THE JOULE-THOMSON AND JOULE COEFFICIENTS AT ONE ATMOSPHERE PRESSURE

Joule-Thomson Coefficient, μ in K/atm

Joule Coefficient, η in K/atm

Temp K	$-\mu_{exp}$	$-\mu_{calc}$	η_{exp}	η_{calc}
273.15	.0616	.0454	−.00404	.00260
223.15	.0606	.0455	−.00133	.00265
173.15	.0584	.0455	.00237	.00270
133.15	.0540	.0446	.00785	.00333
118.15	.0503	.0436	.0107	.00400
93.15	.0412	.0385	.0172	.00705
83.15	.0380	.0340		.00950
70.0		.0245		.0145
60.0		.0132		.0203
55.0		.00570		.0240
50.0		−.00332		.0283

*μ_{exp} as derived from data by Roebuck and Osterberg [16].

*η_{exp} as derived from data by Roebuck and Osterberg [19].

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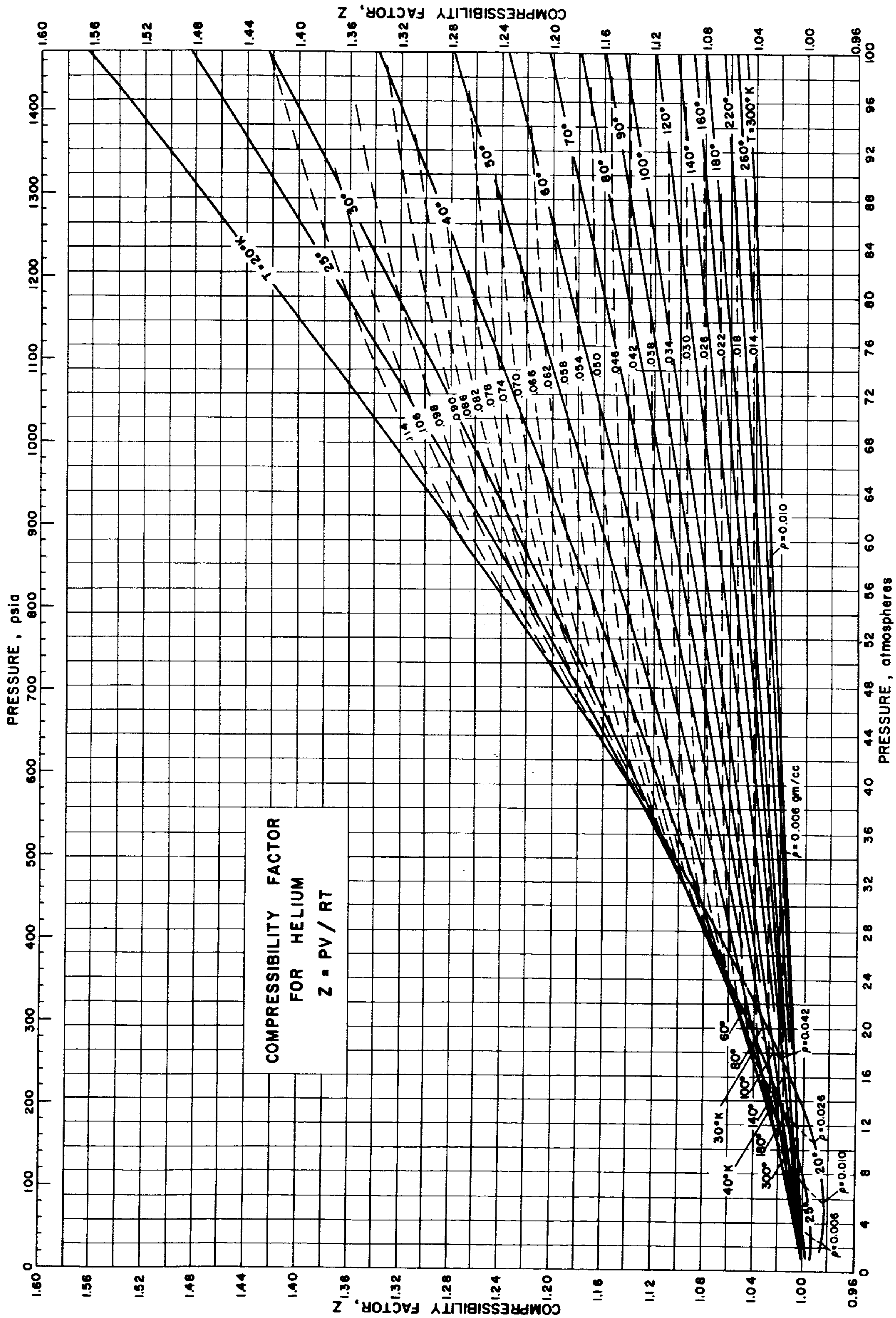
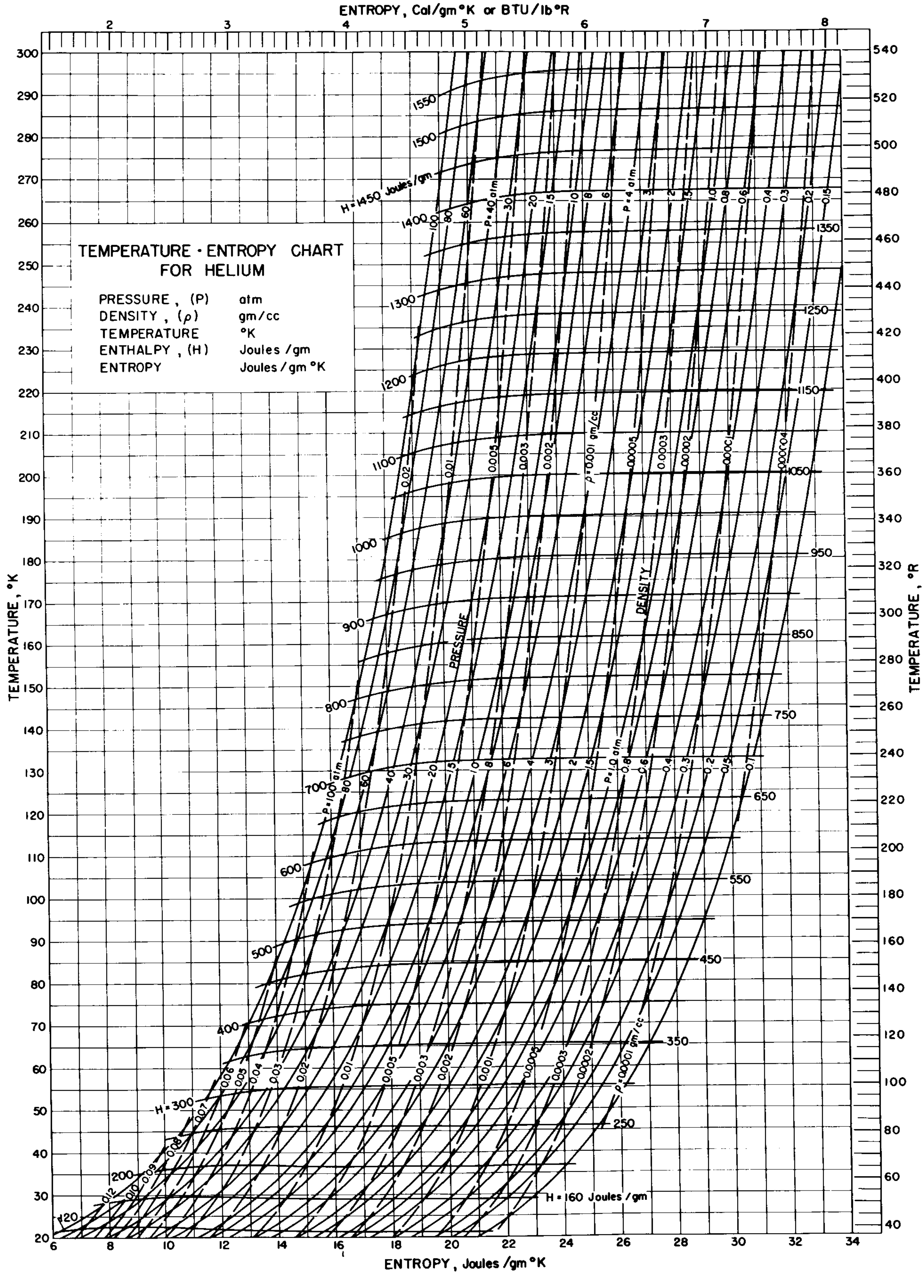

COMPRESSIBILITY FACTOR
FOR HELIUM
Z = PV / RT
PRESSURE , psia
PRESSURE , atmospheres
COMPRESSIBILITY FACTOR, Z
COMPRESSIBILITY FACTOR, Z
T=20°K
T=300°K
ρ=0.006 gm/cc
ρ=0.010
ρ=0.026
ρ=0.042


TEMPERATURE · ENTROPY CHART
FOR HELIUM
PRESSURE , (P) atm
DENSITY , (ρ) gm/cc
TEMPERATURE °K
ENTHALPY , (H) Joules /gm
ENTROPY Joules / gm °K
ENTROPY, Cal/gm °K or BTU/lb °R
ENTROPY, Joules /gm °K
TEMPERATURE, °K
TEMPERATURE, °R
PRESSURE
DENSITY
H=1450 Joules/gm
H=300
H=160 Joules/gm
P=100 atm
P=40 atm
P=4 atm
P=1.0 atm
ρ=0.001 gm/cc
ρ=0.0001 gm/cc

THERMODYNAMIC PROPERTIES OF HELIUM

[ρ = density in gm/cc; h = enthalpy in Joules/gm; s = entropy in Joules/gm°K]

Press. atm.		Temperature in degrees Kelvin 18°	20°	25°	30°	35°	40°	45°	50°	55°	60°	65°
0.1	ρ	.0002710	.0002439	.0001950	.0001625	.0001393	.0001219	.0001083	.00009749	.00008863	.00008124	.00007499
	h	103.1	113.5	139.5	165.5	191.5	217.4	243.4	269.4	295.3	321.3	347.3
	s	20.33	20.88	22.04	22.99	23.79	24.48	25.09	25.64	26.14	26.59	27.00
0.15	ρ	.0004066	.0003658	.0002926	.0002438	.0002089	.0001828	.0001625	.0001462	.0001329	.0001219	.0001125
	h	103.1	113.5	139.5	165.5	191.4	217.4	243.4	269.4	295.3	321.3	347.3
	s	19.49	20.04	21.20	22.14	22.95	23.64	24.25	24.80	25.29	25.75	26.16
0.2	ρ	.0005422	.0004879	.0003901	.0003250	.0002785	.0002437	.0002166	.0001950	.0001772	.0001625	.0001500
	h	103.1	113.5	139.5	165.4	191.4	217.4	243.4	269.4	295.3	321.3	347.3
	s	18.89	19.44	20.60	21.55	22.35	23.04	23.65	24.20	24.70	25.15	25.56
0.3	ρ	.0008137	.0007320	.0005852	.0004875	.0004178	.0003655	.0003249	.0002924	.0002658	.0002437	.0002249
	h	103.0	113.4	139.4	165.4	191.4	217.4	243.4	269.4	295.4	321.3	347.3
	s	18.05	18.59	19.76	20.70	21.50	22.20	22.81	23.36	23.85	24.31	24.72
0.4	ρ	.0010854	.0009763	.0007803	.0006500	.0005570	.0004873	.0004331	.0003898	.0003544	.0003248	.0002998
	h	103.0	113.4	139.4	165.4	191.4	217.4	243.4	269.4	295.4	321.3	347.3
	s	17.45	17.99	19.16	20.10	20.91	21.60	22.21	22.76	23.26	23.71	24.12
0.6	ρ	.0016295	.0014653	.0011706	.0009748	.0008353	.0007307	.0006495	.0005845	.0005314	.0004871	.0004496
	h	102.8	113.3	139.3	165.3	191.3	217.3	243.4	269.4	295.4	321.3	347.3
	s	16.60	17.15	18.31	19.26	20.06	20.76	21.37	21.92	22.41	22.86	23.28
0.8	ρ	.0021744	.0019547	.0015610	.0012996	.0011134	.0009740	.0008657	.0007791	.0007082	.0006492	.0005993
	h	102.7	113.1	139.2	165.2	191.3	217.3	243.3	269.4	295.4	321.4	347.4
	s	16.00	16.55	17.71	18.66	19.46	20.16	20.77	21.32	21.81	22.27	22.68
1.0	ρ	.0027199	.0024445	.0019513	.0016242	.0013914	.0012171	.0010817	.0009735	.0008850	.0008113	.0007489
	h	102.6	113.0	139.1	165.2	191.2	217.3	243.3	269.3	295.4	321.4	347.4
	s	15.53	16.08	17.24	18.19	19.00	19.69	20.31	20.85	21.35	21.80	22.22
1.5	ρ	.0040865	.0036703	.0029269	.0024351	.0020855	.0018240	.0016210	.0014588	.0013263	.0012158	.0011224
	h	102.3	112.8	138.9	165.0	191.1	217.2	243.3	269.3	295.4	321.4	347.4
	s	14.68	15.23	16.39	17.35	18.15	18.85	19.46	20.01	20.51	20.96	21.38
2	ρ	.0054565	.0048978	.0039021	.0032449	.0027783	.0024297	.0021593	.0019432	.0017667	.0016196	.0014952
	h	102.1	112.6	138.7	164.9	191.0	217.2	243.3	269.3	295.4	321.4	347.5
	s	14.07	14.62	15.79	16.74	17.55	18.25	18.86	19.41	19.91	20.36	20.78
3	ρ	.0082041	.0073557	.0058502	.0048607	.0041601	.0036374	.0032323	.0029090	.0026448	.0024248	.0022387
	h	101.6	112.1	138.4	164.6	190.9	217.1	243.2	269.3	295.5	321.5	347.6
	s	13.21	13.76	14.93	15.89	16.70	17.40	18.01	18.56	19.06	19.52	19.93
4	ρ	.010959	.0098151	.0077939	.0064708	.0055361	.0048398	.0043007	.0038705	.0035192	.0032267	.0029794
	h	101.1	111.7	138.0	164.4	190.7	217.0	243.2	269.4	295.5	321.6	347.7
	s	12.59	13.14	14.32	15.28	16.09	16.79	17.41	17.96	18.46	18.92	19.33
6	ρ	.016474	.014728	.011664	.0096714	.0082696	.0072280	.0064227	.0057809	.0052569	.0048208	.0044521
	h	100.2	110.8	137.4	163.9	190.4	216.8	243.1	269.4	295.7	321.9	348.0
	s	11.71	12.27	13.45	14.42	15.23	15.94	16.56	17.11	17.61	18.07	18.49
8	ρ	.021978	.019619	.015503	.012843	.010977	.0095930	.0085246	.0076738	.0069795	.0064018	.0059133
	h	99.38	110.1	136.8	163.5	190.1	216.7	243.1	269.5	295.8	322.1	348.3
	s	11.07	11.63	12.83	13.80	14.62	15.33	15.95	16.51	17.01	17.47	17.89
10	ρ	.027445	.024471	.019305	.015981	.013655	.011934	.010606	.0095490	.0086868	.0079694	.0073628
	h	98.62	109.4	136.3	163.1	189.9	216.6	243.1	269.6	296.0	322.3	348.6
	s	10.57	11.14	12.34	13.32	14.14	14.86	15.48	16.04	16.54	17.00	17.42
15	ρ	.040830	.036344	.028608	.023664	.020220	.017677	.015718	.014159	.012888	.011830	.010936
	h	97.00	107.9	135.2	162.4	189.5	216.5	243.3	270.0	296.6	323.0	349.4
	s	9.647	10.22	11.44	12.43	13.27	13.99	14.62	15.18	15.69	16.15	16.57
20	ρ	.053617	.047717	.037566	.031090	.026585	.023258	.020696	.018657	.016994	.015609	.014437
	h	95.72	106.8	134.4	161.9	189.3	216.5	243.5	270.4	297.2	323.8	350.3
	s	8.977	9.559	10.79	11.79	12.64	13.37	14.00	14.57	15.08	15.54	15.97
30	ρ	.076813	.068563	.054273	.045094	.038676	.033922	.030248	.027318	.024922	.022924	.021230
	h	94.03	105.3	133.4	161.5	189.3	216.9	244.4	271.6	298.6	325.5	352.2
	s	8.014	8.608	9.864	10.89	11.74	12.48	13.13	13.70	14.22	14.69	15.11
40	ρ	.096520	.086648	.069272	.057925	.049905	.043918	.039266	.035540	.032482	.029924	.027750
	h	93.28	104.7	133.3	161.7	189.9	217.8	245.5	273.0	300.3	327.4	354.3
	s	7.323	7.925	9.199	10.23	11.10	11.85	12.50	13.08	13.60	14.07	14.50
60	ρ	.12657	.11524	.094441	.080237	.069894	.062008	.055783	.050737	.046557	.043033	.040020
	h	93.93	105.6	134.6	163.5	192.2	220.6	248.7	276.6	304.2	331.5	358.7
	s	6.352	6.965	8.262	9.316	10.20	10.96	11.62	12.21	12.73	13.21	13.65
80	ρ	.14762	.13620	.11435	.098724	.086982	.077821	.070462	.064415	.059353	.055049	.051342
	h	96.55	108.3	137.6	166.8	195.7	224.4	252.8	280.9	308.7	336.2	363.5
	s	5.678	6.297	7.606	8.670	9.563	10.33	11.00	11.59	12.12	12.60	13.03
100	ρ	.16318	.15330	.13042	.11423	.10170	.091710	.083552	.076759	.071012	.066083	.061807
	h	100.4	112.2	141.7	171.0	200.1	228.9	257.4	285.6	313.6	341.2	368.6
	s	5.170	5.792	7.107	8.176	9.074	9.843	10.51	11.11	11.64	12.12	12.56

THERMODYNAMIC PROPERTIES OF HELIUM

[ρ = density in gm/cc; h = enthalpy in Joules/gm; s = entropy in Joules/gm°K]

Press.		Temperature in degrees Kelvin										
atm.		70°	75°	80°	85°	90°	95°	100°	110°	120°	130°	140°
0.1	ρ	.00006964	.00006500	.00006093	.00005735	.00005416	.00005131	.00004875	.00004432	.00004062	.00003750	.00003482
	h	373.3	399.2	425.2	451.2	477.1	503.1	529.1	581.0	633.0	684.9	736.8
	s	27.39	27.75	28.08	28.40	28.69	28.98	29.24	29.74	30.19	30.60	30.99
0.15	ρ	.0001045	.00009749	.00009139	.00008602	.00008124	.00007697	.00007312	.00006647	.00006093	.00005625	.00005223
	h	373.3	399.2	425.2	451.2	477.2	503.1	529.1	581.0	633.0	684.9	736.8
	s	26.55	26.91	27.24	27.56	27.85	28.13	28.40	28.89	29.35	29.76	30.15
0.2	ρ	.0001393	.0001300	.0001219	.0001147	.0001083	.0001026	.00009749	.00008862	.00008124	.00007499	.00006964
	h	373.3	399.2	425.2	451.2	477.2	503.1	529.1	581.0	633.0	684.9	736.8
	s	25.95	26.31	26.64	26.96	27.25	27.54	27.80	28.30	28.75	29.16	29.55
0.3	ρ	.0002089	.0001949	.0001828	.0001720	.0001625	.0001539	.0001462	.0001329	.0001219	.0001125	.0001045
	h	373.3	399.3	425.2	451.2	477.2	503.1	529.1	581.1	633.0	684.9	736.9
	s	25.11	25.46	25.80	26.12	26.41	26.69	26.96	27.45	27.91	28.32	28.71
0.4	ρ	.0002784	.0002599	.0002436	.0002293	.0002166	.0002052	.0001949	.0001772	.0001625	.0001500	.0001393
	h	373.3	399.3	425.2	451.2	477.2	503.2	529.1	581.1	633.0	685.0	736.9
	s	24.51	24.87	25.20	25.52	25.81	26.10	26.36	26.86	27.31	27.72	28.11
0.6	ρ	.0004175	.0003897	.0003654	.0003439	.0003248	.0003077	.0002923	.0002658	.0002436	.0002249	.0002088
	h	373.3	399.3	425.3	451.3	477.2	503.2	529.2	581.1	633.1	685.0	736.9
	s	23.67	24.02	24.36	24.67	24.97	25.25	25.52	26.01	26.47	26.88	27.27
0.8	ρ	.0005565	.0005195	.0004870	.0004584	.0004329	.0004102	.0003897	.0003543	.0003248	.0002998	.0002784
	h	373.3	399.3	425.3	451.3	477.3	503.2	529.2	581.2	633.1	685.0	737.0
	s	23.07	23.43	23.76	24.08	24.37	24.65	24.92	25.42	25.87	26.28	26.67
1.0	ρ	.0006954	.0006491	.0006086	.0005728	.0005410	.0005126	.0004870	.0004428	.0004059	.0003747	.0003480
	h	373.4	399.4	425.3	451.3	477.3	503.3	529.3	581.2	633.1	685.1	737.0
	s	22.60	22.96	23.30	23.61	23.91	24.19	24.46	24.95	25.40	25.82	26.21
1.5	ρ	.0010423	.0009729	.0009122	.0008586	.0008110	.0007684	.0007300	.0006638	.0006085	.0005618	.0005217
	h	373.4	399.4	425.4	451.4	477.4	503.4	529.4	581.3	633.3	685.2	737.1
	s	21.76	22.12	22.46	22.77	23.07	23.35	23.62	24.11	24.56	24.98	25.36
2	ρ	.0013886	.0012962	.0012153	.0011440	.0010806	.0010238	.0009728	.0008845	.0008109	.0007487	.0006953
	h	373.5	399.5	425.5	451.5	477.5	503.5	529.5	581.4	633.4	685.3	737.3
	s	21.16	21.52	21.86	22.17	22.47	22.75	23.02	23.51	23.96	24.38	24.77
3	ρ	.0020793	.0019411	.0018202	.0017134	.0016186	.0016337	.0014572	.0013252	.0012151	.0011219	.0010419
	h	373.6	399.7	425.7	451.7	477.7	503.7	529.7	581.7	633.6	685.6	737.5
	s	20.32	20.68	21.01	21.33	21.63	21.91	22.17	22.67	23.12	23.54	23.92
4	ρ	.0027674	.0025837	.0024230	.0022811	.0021549	.0020420	.0019404	.0017647	.0016183	.0014943	.0013879
	h	373.8	399.9	425.9	451.9	477.9	503.9	529.9	581.9	633.9	685.8	737.8
	s	19.72	20.08	20.42	20.73	21.03	21.31	21.58	22.07	22.52	22.94	23.32
6	ρ	.0041361	.0038623	.0036226	.0034110	.0032228	.0030544	.0029027	.0026406	.0024219	.0022367	.0020778
	h	374.1	400.2	426.3	452.3	478.4	504.4	530.4	582.4	634.4	686.3	738.3
	s	18.88	19.24	19.57	19.89	20.19	20.47	20.73	21.23	21.68	22.10	22.48
8	ρ	.0054946	.0051318	.0048141	.0045337	.0042842	.0040609	.0038598	.0035120	.0032218	.0029759	.0027649
	h	374.5	400.6	426.7	452.8	478.8	504.9	530.9	582.9	634.9	686.9	738.8
	s	18.28	18.64	18.97	19.29	19.59	19.87	20.14	20.63	21.08	21.50	21.88
10	ρ	.0068429	.0063922	.0059976	.0056491	.0053391	.0050615	.0048115	.0043789	.0040179	.0037119	.00344[illegible]
	h	374.8	401.0	427.1	453.2	479.3	505.4	531.4	583.4	635.4	687.4	739.[illegible]
	s	17.81	18.17	18.51	18.82	19.12	19.40	19.67	20.17	20.62	21.04	21.42
15	ρ	.010169	.0095038	.0089211	.0084063	.0079481	.0075375	.0071675	.0065269	.0059918	.0055378	.0051479
	h	375.8	402.0	428.2	454.4	480.5	506.6	532.7	584.8	636.8	688.8	740.8
	s	16.96	17.32	17.66	17.98	18.28	18.56	18.83	19.32	19.78	20.19	20.58
20	ρ	.013432	.012560	.011795	.011119	.010517	.0099774	.0094907	.0086476	.0079424	.0073439	.0068293
	h	376.7	403.1	429.4	455.6	481.8	507.9	534.0	586.1	638.2	690.2	742.2
	s	16.36	16.72	17.06	17.38	17.68	17.96	18.23	18.73	19.18	19.60	19.98
30	ρ	.019774	.018509	.017398	.016415	.015538	.014751	.014041	.012808	.011775	.010897	.010141
	h	378.8	405.3	431.7	458.0	484.3	510.5	536.6	588.9	641.0	693.0	745.1
	s	15.51	15.87	16.21	16.53	16.83	17.12	17.38	17.88	18.34	18.75	19.14
40	ρ	.025878	.024247	.022814	.021543	.020408	.019388	.018466	.016864	.015520	.014374	.013387
	h	381.0	407.6	434.1	460.5	486.9	513.1	539.3	591.6	643.8	695.9	747.9
	s	14.90	15.27	15.61	15.93	16.23	16.52	16.78	17.28	17.74	18.15	18.54
60	ρ	.037412	.035130	.033116	.031324	.029719	.028273	.026962	.024678	.022753	.021108	.019686
	h	385.7	412.5	439.1	465.7	492.1	518.5	544.8	597.3	649.5	701.7	753.8
	s	14.05	14.41	14.76	15.08	15.38	15.67	15.94	16.44	16.89	17.31	17.70
80	ρ	.048114	.045276	.042760	.040514	.038496	.036671	.035014	.032116	.029664	.027563	.025740
	h	390.6	417.6	444.4	471.0	497.6	524.0	550.4	602.9	655.3	707.5	759.6
	s	13.44	13.81	14.15	14.48	14.78	15.07	15.34	15.84	16.29	16.71	17.10
100	ρ	.058061	.054751	.051803	.049162	.046780	.044622	.042655	.039205	.036276	.033756	.031566
	h	395.8	422.9	449.7	476.5	503.1	529.6	556.0	608.6	661.1	713.3	765.5
	s	12.97	13.34	13.68	14.01	14.31	14.60	14.87	15.37	15.83	16.25	16.63

THERMODYNAMIC PROPERTIES OF HELIUM

[ρ = density in gm/cc; h = enthalpy in Joules/gm; s = entropy in Joules/gm°K]

Press. atm.		Temperature in degrees Kelvin 150°	160°	170°	180°	190°	200°	220°	240°	260°	280°	300°
0.1	ρ	.00003250	.00003047	.00002868	.00002708	.00002566	.00002437	.00002216	.00002031	.00001875	.00001741	.00001625
	h	788.8	840.7	892.6	944.6	996.5	1048.4	1152.3	1256.2	1360.1	1463.9	1567.8
	s	31.35	31.68	32.00	32.29	32.58	32.84	33.34	33.79	34.20	34.59	34.95
0.15	ρ	.00004875	.00004570	.00004301	.00004062	.00003849	.00003656	.00003324	.00003047	.00002812	.00002612	.00002437
	h	788.8	840.7	892.6	944.6	996.5	1048.5	1152.3	1256.2	1360.1	1463.9	1567.8
	s	30.51	30.84	31.16	31.45	31.73	32.00	32.49	32.95	33.36	33.75	34.11
0.2	ρ	.00006499	.00006093	.00005735	.00005416	.00005131	.00004875	.00004432	.00004062	.00003750	.00003482	.00003250
	h	788.8	840.7	892.7	944.6	996.5	1048.5	1152.3	1256.2	1360.1	1464.0	1567.8
	s	29.91	30.24	30.56	30.85	31.14	31.40	31.90	32.35	32.76	33.15	33.51
0.3	ρ	.00009748	.00009139	.00008602	.00008124	.00007696	.00007312	.00006647	.00006093	.00005625	.00005223	.00004875
	h	788.8	840.7	892.7	944.6	996.5	1048.5	1152.4	1256.2	1360.1	1464.0	1567.8
	s	29.07	29.40	29.72	30.01	30.29	30.56	31.05	31.51	31.92	32.31	32.67
0.4	ρ	.0001300	.0001219	.0001147	.0001083	.0001026	.00009748	.00008862	.00008124	.00007499	.00006964	.00006499
	h	788.8	840.8	892.7	944.6	996.6	1048.5	1152.4	1256.3	1360.1	1464.0	1567.9
	s	28.47	28.80	29.12	29.41	29.70	29.96	30.46	30.91	31.32	31.71	32.07
0.6	ρ	.0001949	.0001828	.0001720	.0001625	.0001539	.0001462	.0001329	.0001219	.0001125	.0001044	.00009748
	h	788.9	840.8	892.7	944.7	996.6	1048.6	1152.4	1256.3	1360.2	1464.0	1567.9
	s	27.63	27.96	28.28	28.57	28.85	29.12	29.61	30.07	30.48	30.87	31.22
0.8	ρ	.0002599	.0002436	.0002293	.0002166	.0002052	.0001949	.0001772	.0001625	.0001500	.0001393	.0001300
	h	788.9	840.9	892.8	944.7	996.7	1048.6	1152.5	1256.3	1360.2	1464.1	1568.0
	s	27.03	27.36	27.68	27.97	28.26	28.52	29.02	29.47	29.88	30.27	30.63
1.0	ρ	.0003248	.0003045	.0002866	.0002707	.0002564	.0002436	.0002215	.0002030	.0001874	.0001740	.0001625
	h	789.0	840.9	892.8	944.8	996.7	1048.6	1152.5	1256.4	1360.3	1464.1	1568.0
	s	26.56	26.90	27.21	27.51	27.79	28.06	28.55	29.00	29.42	29.81	30.16
1.5	ρ	.0004870	.0004566	.0004297	.0004059	.0003845	.0003653	.0003321	.0003045	.0002811	.0002610	.0002436
	h	789.1	841.0	893.0	944.9	996.8	1048.8	1152.6	1256.5	1360.4	1464.3	1568.1
	s	25.72	26.06	26.37	26.67	26.95	27.22	27.71	28.16	28.58	28.96	29.32
2	ρ	.0006490	.0006085	.0005728	.0005410	.0005125	.0004869	.0004427	.0004059	.0003747	.0003479	.0003248
	h	789.2	841.1	893.1	945.0	997.0	1048.9	1152.8	1256.6	1360.5	1464.4	1568.2
	s	25.12	25.46	25.77	26.07	26.35	26.62	27.11	27.56	27.98	28.37	28.72
3	ρ	.0009726	.0009120	.0008585	.0008109	.0007683	.0007299	.0006637	.0006085	.0005617	.0005217	.0004869
	h	789.5	841.4	893.3	945.3	997.2	1049.1	1153.0	1256.9	1360.8	1464.6	1568.5
	s	24.28	24.62	24.93	25.23	25.51	25.78	26.27	26.72	27.14	27.52	27.88
4	ρ	.0012957	.0012150	.0011437	.0010803	.0010236	.0009726	.0008844	.0008108	.0007486	.0006952	.0006489
	h	789.7	841.7	893.6	945.5	997.5	1049.4	1153.3	1257.1	1361.0	1464.9	1568.8
	s	23.68	24.02	24.33	24.63	24.91	25.18	25.67	26.12	26.54	26.93	27.28
6	ρ	.0019400	.0018193	.0017128	.0016180	.0015332	.0014569	.0013249	.0012148	.0011217	.0010418	.0009725
	h	790.2	842.2	894.1	946.1	998.0	1049.9	1153.8	1257.7	1361.6	1465.4	1569.3
	s	22.84	23.18	23.49	23.79	24.07	24.34	24.83	25.28	25.70	26.08	26.44
8	ρ	.0025818	.0024215	.0022800	.0021540	.0020413	.0019398	.0017643	.0016179	.0014940	.0013877	.0012955
	h	790.8	842.7	894.7	946.6	998.5	1050.5	1154.4	1258.2	1362.1	1466.0	1569.8
	s	22.24	22.58	22.89	23.19	23.47	23.74	24.23	24.68	25.10	25.48	25.84
10	ρ	.0032213	.0030216	.0028453	.0026884	.0025479	.0024213	.0022025	.0020200	.0018654	.0017328	.0016178
	h	791.3	843.3	895.2	947.2	999.1	1051.0	1154.9	1258.8	1362.7	1466.5	1570.4
	s	21.78	22.11	22.43	22.73	23.01	23.27	23.77	24.22	24.64	25.02	25.38
15	ρ	.0048093	.0045125	.0042502	.0040167	.0038076	.0036192	.0032932	.0030211	.0027905	.0025927	.0024210
	h	792.7	844.7	896.6	948.6	1000.5	1052.5	1156.3	1260.2	1364.1	1467.9	1571.8
	s	20.94	21.27	21.59	21.88	22.16	22.43	22.93	23.38	23.79	24.18	24.54
20	ρ	.0063822	.0059901	.0056434	.0053346	.0050579	.0048084	.0043767	.0040162	.0037105	.0034481	.0032203
	h	794.2	846.1	898.1	950.0	1001.9	1053.9	1157.8	1261.6	1365.5	1468.4	1573.3
	s	20.34	20.67	20.99	21.29	21.57	21.83	22.33	22.78	23.20	23.58	23.94
30	ρ	.0094835	.0089059	.0083946	.0079389	.0075302	.0071614	.0065227	.0059885	.0055352	.0051457	.0048075
	h	797.0	849.0	901.0	952.9	1004.9	1056.8	1160.7	1264.5	1368.4	1472.3	1576.2
	s	19.50	19.83	20.15	20.44	20.72	20.99	21.49	21.94	22.35	22.74	23.10
40	ρ	.012526	.011770	.011100	.010502	.0099654	.0094809	.0086407	.0079373	.0073398	.0068260	.0063794
	h	799.9	851.9	903.9	955.8	1007.8	1059.7	1163.6	1276.5	1371.4	1475.2	1579.1
	s	18.90	19.23	19.55	19.85	20.13	20.39	20.89	21.34	21.76	22.14	22.50
60	ρ	.018443	.017349	.016377	.015509	.014728	.014022	.012795	.011766	.010890	.010135	.0094782
	h	805.8	857.8	909.8	961.8	1013.7	1065.7	1169.6	1273.4	1377.3	1481.2	1585.0
	s	18.06	18.39	18.71	19.00	19.28	19.55	20.05	20.50	20.91	21.30	21.66
80	ρ	.024145	.022736	.021483	.020361	.019350	.018436	.016843	.015504	.014362	.013377	.012518
	h	811.7	863.7	915.7	967.7	1019.7	1071.6	1175.5	1279.4	1383.3	1487.2	1591.0
	s	17.46	17.79	18.11	18.41	18.69	18.95	19.45	19.90	20.32	20.70	21.06
100	ρ	.029643	.027942	.026426	.025066	.023840	.022728	.020789	.019155	.017760	.016554	.015501
	h	817.6	869.7	921.7	973.7	1025.7	1077.6	1181.5	1285.4	1389.3	1493.2	1597.1
	s	16.99	17.33	17.64	17.94	18.22	18.49	18.98	19.44	19.85	20.24	20.60

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